Techno-economic assessment of semi-submersible FOWT concepts

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Abstract

The objective of the present thesis is to assess the possibility of a more accurate and trustful methodology regarding the annual energy production estimation of a floating wind turbine. The conventional approach is to integrate the turbine's power curve along a given Weibull wind distribution. The alternative proposed involves the use of numerical simulations with the OpenFAST code. Furthermore, an economic sensitiveness analysis is performed, with a suitable model from WavEC.

An introduction to the renewable energies field is presented, which ends tilting towards a discussion on present challenges and endeavours regarding the wind power industry. Special focus is attributed to its floating offshore sector.

The numerical tool is explored through the analysis of the set of modules that constitute it. The goal is to reach a more accurate and confident framing of the final results through the evaluation of the computer-implemented models and assumptions considered. Following, consistency tests are carried out in order to numerically check the model's validity.

Finally, the energy topic is dealt with and compared for the two suggested approaches. An economic analysis aiming at assessing the LCOE's sensitiveness to some determining factors is also presented. Such study also allows an insight into the relevance of the numerical approach proposed.

Keywords: Renewable energies, energy production estimation, floating wind turbines, numerical methods, economic analysis

1. Introduction

1.1. Renewable energies frame

Undeniably, environment awareness and a responsible energetic resource exploration, commercialization and utilization is on the forefront of the global political and economic agenda. International groups, organizations, institutions as well as governments are increasingly more committed to take serious action in regard to a clean energy transition, to replace fossil fuels and to preserve earth's fragile equilibrium. But current communities concerns go beyond that. An holistic overview of the energetic issue calls for a more integrated answer, highlighting factors such as inter- and intra-national social justice and well being on the broader discussion. Such trend manifestations can be found at high political levels, such as the Paris agreement; at popular demonstrations, patent in the many climate strikes that are taking place worldwide; or even in relevant spiritual leaders documents, such as Pope Francis' *Laudato Si* encyclical, whose subtitle is "on care for our common house". It is in this framing that a strong push towards new, more reliable and more efficient renewable energies has been taking place in the last few years, with an ever increasing acceleration. This phenomena is patent in figure 1.

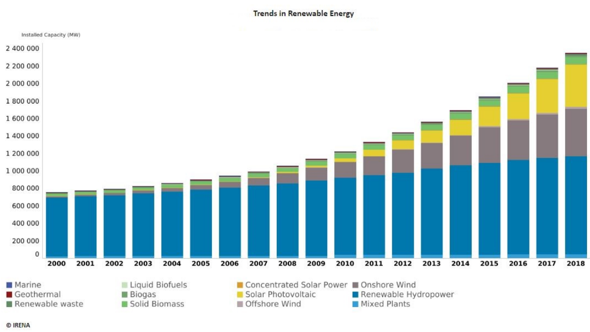

Figure 1: Renewable installed capacity growth in [1]

1.2. Floating offshore wind energy motivation

One fundamental part in this broad process is wind energy. If is true that onshore wind has played an undisputed leading role in this industry, more option are becoming a luring option. Offshore bottom-fixed wind is already a suitable commercial way of exploring wind resources. But either onshore as well as bottom-fixed wind have important physical and geographical constraints regarding its expansion. On the other hand, the enormous deep-offshore wind potential, which represents an almost endless power source, as presented in table 1, constitutes a strong driver for harnessing its power. Along with other advantages such as stronger, more stable and predictable wind conditions, this huge potential makes offshore floating wind to be looked upon as a likely key energy supplier in the future.

Region or country	Share of deep OW (+60m)	FOW potential
Europe	80%	4000 GW
USA	60%	2450 GW
Japan	80%	500GW

Table 1: Potential for floating offshore wind, in [2]
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The possibility to harness this otherwise impossible source of energy and thus providing a sustainable and safe energetic future is what constitutes the main motivation for studying and developing floating offshore wind.

1.3. State of the art
Floating offshore wind doesn't yet offer a commercial and experienced way of exploring offshore energy. There are a few innovative wind farms such as WindFloat Atlantic and Hywind but they are far from being mainstream and their LCOE isn't yet competitive. Currently, bottom-fixed wind is the only sufficiently mature technology to be economically explored offshore. The main constraint defining which of these two can be used is water depth. In fact, bottom-fixed structures cannot be used in waters deeper than about 40 to 50m [3]. Present day main offshore structures types are displayed in figure 2.

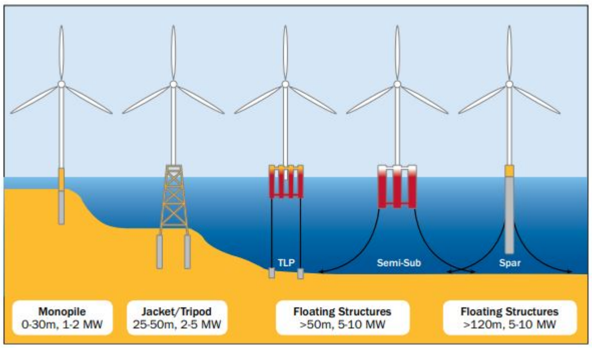


Figure 2: Typical offshore wind structures in [3].

Although there are some exceptions, the overwhelming majority of turbine designs are three-bladed upwind. The offshore wind industry has been witnessing a big increase in regard to turbines size and rated power. In four years the average newly installed capacity of offshore turbines, more than doubled [4]. Main concepts' technological readiness level have been steadily increasing for the last few years, enabling a near future possible suitability for large scale projects, a trend that is confirmed by the over 350 MW of announced floating wind pre-commercial projects announced until 2022. This represents an increase of more than 1200% in regard to 2019.

1.4. Objectives
In light of the challenges and motivation described, the present work has two main objectives. Firstly, to explore the possibility of a more accurate turbine energy output estimation method in the floating case. In such field the sea dynamics play an important role in a turbine overall performance. Thus, the need to estimate the extent of its influence and compare it to a typical method of integrating a given wind distribution on a turbine power curve and assess its validity in a floating situation. Moreover, a detailed research aiming to breakdown the floating turbine dynamics and find the main power reduction factors is carried out. This is achieved with a simulation-based approach relying on OpenFAST code. The second objective is to perform a sensitivity analysis of the LCOE (levelized cost of energy) of a floating wind turbine in order to discuss and understand how extensively each cost parameter influences the final cost. It also enables a perspective on the relevance of the differences found between the capacity factors arising from the first objective.

1.5. OC4 semisubersible model
The semisubmersible floating system designed for OC4 project is the model utilized in this work. It is constituted by NREL's 5MW baseline turbine; by a semisubersible floating concept designed for the DeepCWind project and by a catenary mooring system with three lines. OC4 phase II task consisted in a set of tests to check the model correctness, of which some are mentioned throughout this work and can be found in [5].In it, LC stands for load case.

2. Model mathematical formulation

The numerical tool OpenFast is constituted by different modules coupled to each other, being each responsible for specific turbine dynamics.

2.1. Aerodyn v15
AeroDyn v15 is a time-domain wind turbine aerodynamics module that enables aero-elastic simulation of horizontal-axis wind turbines. It has four submodule within: blade airfoil aerodynamics, in which calculations are based on the principle of actuator lines which approximates 3D flow around a body with a set of 2D flows at cross sections; blade rotor wake/induction, which uses a methodology based on the Blade Element/Momentum theory; tower influence on the wind close to the blade nodes, which is based on a potential-flow, as an upwind rotor is used; tower drag, which is based on the tower diameter, drag coefficient and the local relative wind velocity.

2.2. Hydrodyn v2.03

HydroDyn is a time-domain hydrodynamics module that has been coupled into OpenFAST wind turbine CAE tool to enable aero-hydro-servoelastic simulation of offshore wind turbines. The equation describing the forces acting on the floating platform is:

$$F_{platf} = F_{hydro} + F_{moorings} + F_{aero} \tag{1}$$

To approach the hydrodynamic loads problem, a linearization is carried out, as its integrated nature is divided into the following forces:

Firstly, radiation arising from added mass and wave damping coefficients. Mathematically it is given by equation 2

$$F_{rad} = -A_{\infty}\ddot{q}(t) - F_{RD} \tag{2}$$

In which A_{∞} is the infinite-frequency added mass; $\ddot{q}(t)$ denotes the complex displacement vector; and F_{RD} is the radiation memory-effect force given by equation 3

$$F_{RD} = \int_0^t K(t-\tau)\dot{q}(\tau)d\tau \tag{3}$$

Where τ is a dummy variable with the same units as the time variable t and $K_{i,j}(t)$ is the kernel of the convolution term that represents the matrix of retardation. It accounts for the hydrodynamic force in i direction, resulting from a unit impulse in j direction, at a time t. The kernel is obtained through the cosine transform of the 6x6 frequency-dependent hydrodynamic damping and added mass matrix from the radiation problem and decays to zero after a short amount of time.

Secondly, excitation force obtained from Froude-Krylov (due to unsteady pressure field generated by undisturbed waves.) and diffraction forces (accounts for the body effect on the incoming waves). It's put mathematically in equation 4:

$$F_{exc} = A_{wave}e^{iwt} * \hat{f}_{exc}(w,\beta) \tag{4}$$

Being A_{wave} the wave amplitude, w the wave frequency and $\hat{f}_{exc}$ the complex wave excitation force per unit wave amplitude.

There is also the linearized hydrostatic restoring due to the balance between buoyancy and weight, as patent in equation 5

$$F_{hydrostatic} = \rho g V_0 - C_{hydrostatic}q \tag{5}$$

Where V_0 is the displaced volume of water at the platform undisplaced position and $C_{hydrostatic}$ is the linear hydrostatic-restoring matrix.

Finally, sea current and other non-linear effects are considered. To grasp this kind of effects that potential theory cannot incorporate, a corrective term from Morrison's equation is used. It has a series of limitations concerning its utilization on its own. Nevertheless, the nonlinear viscous drag term has been included (by assigning an effective platform diameter, D) due to the importance of this source of drag in the general platform dynamics and damping. Equation 6 defines the infinitesimal force for a given moment t, depth z and DOF direction i.

$$dF_i^{viscous} = \frac{1}{2}C_D\rho D dz[v_i - \dot{q}_i]|v_i - \dot{q}_i| \tag{6}$$

Where C_D is the normalized viscous drag coefficient, v is the undisturbed fluid velocity. For the complete nonlinear viscous force, it's necessary to integrate the equation through the floater's entire draft, what requires the use of strip theory.

Hydrodyn treats waves using first-order (linear Airy) and is able to model regular (periodic) or irregular (stochastic, a superposition of regular waves) and shortcrested (wave energy is spread across a range of directions)or long-crested (unidirectional) waves. The deep water hypothesis is assumed throughout the work. Regular waves surface elevation is patent in equation 7

$$\eta(x,t) = A_{wave}cos(kx - wt) \tag{7}$$

Where k is the angular wave number given in equation 8. λ stands for the wave wavelength.

$$k = \frac{2\pi}{\lambda} \tag{8}$$

In order to ensure a valid deep water assumption equation 9 must be observed where d stands for water depth.

$$\frac{d}{\lambda} > 0,5 \tag{9}$$

2.3. Other modules

Elastodyn v1.03 is a structural-dynamic model for HAWT (horizontal axis wind turbine). It has structural modules for the tower, platform, nacelle, drivetrain and rotor. It is comprised of 16 DOF's plus the 6 DOF's associated with the platform displacements and rotations. Bernoulli-Euler beam theory is applied for the rotor blades and beams are considered to be made of isotropic material and without mass or elastic offset.

Moordyn is an open source lumped-mass mooring line discretized model. The physical model accounts for internal axial stiffness and damping forces; weight and buoyancy forces; hydrodynamic forces from Morison equation; vertical spring-damper forces from contact with the seabed; and wake kinematics (from Hydrodyn) interactions with the mooring lines.

In Servodyn v1.05, a conventional variable-speed, variable blade-pitch-to-feather control configuration has been adopted. Accordingly, two basic control systems are applied: a generator-torque controller for the under-rated wind speed regime and a blade-pitch controller for the over-rated wind speed range.

InflowWind is the module used for processing wind-inflow that has been coupled into OpenFAST. It's the module that specifies all characteristics of the wind flow with which the turbine will interact.

2.4. WAMIT

WAMIT role is to provide the linearised hydrodynamic and hydrostatic coefficients, which Hydrodyn uses as inputs in order to solve the linearised hydrodynamic problem. WAMIT assumes the flow to be potential and for solving the radiation and excitation problem, equation 10 must be observed with an adequate set of linearized boundary conditions. MSL is at $z = 0$ and the sea bed is at $z = -d$. $\eta(x, t)$ is the free surface elevation. 2D simplification is used in the the set of equations.

Laplace equation:

$$\nabla^2 \Phi = 0 \tag{10}$$

Kinematic bottom boundary condition:

$$\frac{\partial \Phi}{\partial z} = 0 \qquad at \quad z = -d \tag{11}$$

Kinematic free-surface boundary condition:

$$\frac{\partial \Phi}{\partial z} = \frac{\partial \eta}{\partial z} \qquad at \quad z = \eta(x, t) \tag{12}$$

Dynamic free surface boundary condition:

$$\frac{\partial \Phi}{\partial t} + g\eta = 0 \qquad at \quad z = \eta(x, t) \tag{13}$$

The total complex potential is the sum of the radiation and excitation potentials. The excitation potential, by its turn is equal to the sum of the Froud-Krylov (or incident wave potential) and diffraction potential:

$$\Phi(x, z, t) = \Phi_R + \Phi_I + \Phi_D \tag{14}$$

When the potential functions are known, the first order hydrodynamic pressure distribution can be calculated. After, forces are calculated by integrating the pressure over the wetted surface of the body and enabling the creation of the desired coefficients. Hydrostatic restoring accounts for the restoring provided by buoyancy.

3. Validation and consistency tests

In this chapter, the main goal is to better understand and validate the behaviour of the simulated floating wind turbine through a series of simulations that focus on key aspects of the structure dynamics. Progressively, the number of enabled DOF's increases.

3.1. Decay tests

Decay tests have been run for the 6 DOF's of the rigid floating structure with only the platform and moorings DOF's enabled. The checking procedure consists in observing whether the results obtained in this free-decay test match those that arose from the OC4 project. For such, an analysis of the mean vibration frequencies of the 6 rigid body DOF's, has been performed. Both results matched. Some insights confirmed the non-linear nature of the drag and mooring line force.

3.2. Coupling analysis

Regarding the interconnection of the platform DOF's a coupling analysis has been performed using the decayment tests as basis. The major dependencies were found to be the dependence of Pitch with Surge; Roll with Sway; and of Sway on Surge (unilaterally). Very interestingly, the first two interdependencies were expectable due to the added mass and damping coefficient matrices values. These matrices also lead to other couplings, though less strong, patent in the analysis performed. But the effect Sway has on Surge isn't explainable in regard to the matrices. It's the asymmetric layout of the mooring lines that originates it.

3.3. High and low frequency tests

The objective of these load cases is to assess if it platform behaves as expected in such conditions. This means, accompanying the wave elevation in the low frequency case (0.02 Hz) and remaining still when subject to a high frequency wave (0,5 Hz). The platform behaved exactly as it was supposed to, thus fostering the confidence in the model and its correctness. All DOF's have been enabled from this section onwards.

3.4. JONSWAP spectrum tests

In this subsection the simulations carried out involve the use of the JONSWAP spectrum. The purpose is to have a similar case with which the simulations used for calculating the AEP can be compared. At the same time, comparison with available data from OC4 task enables a verification of the model under these conditions. Again, all values are within the expectable results. Throughout the tests, it has been detected a decrease in power production for one simulated case. This anticipates a more complete and deep analysis to take place in the next chapter, while already providing some insight into the possible parameters affecting the power output, such as pitch angle and mean for-aft tower displacement. A definitive conclusion is the importance of integrating the different dynamics present in a floating wind turbine for a more accurate analysis of its overall performance.

4. AEP Calculation, comparison and analysis

Two approaches to calculate the AEP of the proposed wind turbine are compared. The standard one, is to integrate the turbine power curve along the discretized wind's Weibull distribution. This one will be identified as "conventional approach". The other is to perform simulation with FAST using the same wind condition, incorporating the sea kinematics. This one will be identified as "present approach". The difference lies in consideration of the sea-effect in the floating system dynamics, which is expected to jeopardize the turbine's energetic output efficiency.

4.1. Assumptions

The same JONSWAP spectrum will be used for different wind conditions simulations. This means that wind-generated seas are not taken into consideration but swell waves are. There are a set of reasons for this choice: Firstly because the more energetic-relevant waves are swell waves which JONSWAP spectrum captures well, and not those originated by local winds. Secondly, swell waves (as well as the JONSWAP spectrum waves) have lower frequencies, when compared to local waves, much closer to the platform natural frequencies, which is a key factor regarding resonance and consequently has a stronger potential for decreasing energy production. Both remarks become evident in figure 3.

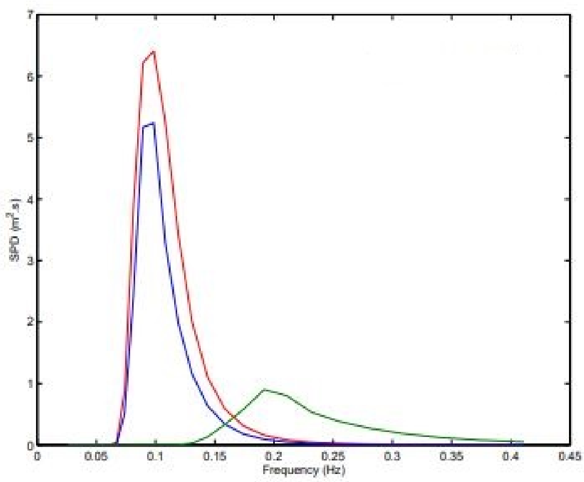


Figure 3: Swell system: blue line, wind sea: green line and fitted JONSWAP spectrum:red line. Results for an analysis in the Bay of Biscay [6]

Other assumptions and simplifications are the wind and wave alignment; the wind distribution discretization into 9 classes; a exponential wind profile without turbulence and wind-shear effects; and the fact that the turbine efficiency is assumed to be 100%.

4.2. Wind resource

A specific location 150 km off the coast of northern Portugal has been chosen as the site whose wind conditions are utilized as a starting point in this work. The final wind distribution used for the approaches comparison is a fitted Weibull distribution based on such data. It is in the range of the most interesting regions of the country regarding offshore wind power potential. The data was obtained from a dedicated wind model, WAVEWATCH III [7], and is deemed adequate for the turbine characteristics.

4.3. Analysis of power reducing factors

4.3.1 Pitch

Following the analysis of three similar yet different simulations with the same external conditions: a fully enabled turbine; a rigid tower turbine; and a rigid, fixed turbine with a mean Pitch value of 3,4°. Through the comparison of these cases responses a set of conclusion have been drawn. Firstly, that the mean Pitch angle is the main responsible for bringing the mean power output down, and not its oscillations. Secondly, The effect of for-aft tower displacement is very reduced. In fact, even the reduced influence it has, arises indirectly from the changes it induces on Pitch, namely, by slightly increasing it. With such remarks established, the interest moves on towards finding the how and to what extent does Pitch mean angle influence the turbine power output. The answer lies in figure 4.

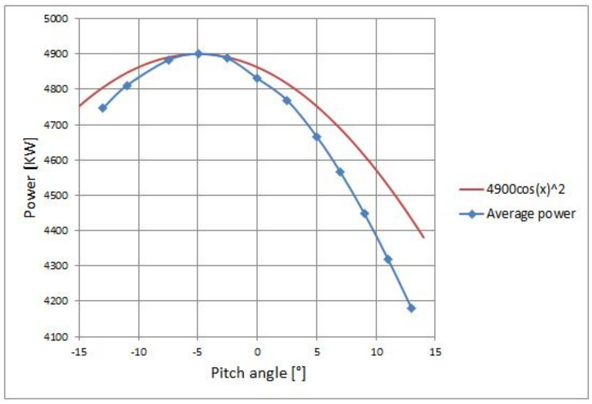


Figure 4: Power production sensitiveness to pitch angle, at rated condition

The reason why the squared cosine function is displayed is because the power depends on the area perpendicular to the wind direction, which by its turn, depends on the square of the rotor diameter, either aligned or not. Mathematically, the general law for wind power :

$$P = \frac{1}{2}\rho A_{perpendicular} U^3 \qquad (15)$$

This equation states the dependence of power with the projected rotor area. The following is the simple circular area equation.

$$A_{perpendicular} = \frac{\pi}{4} D^2_{perpendicular} \quad (16)$$

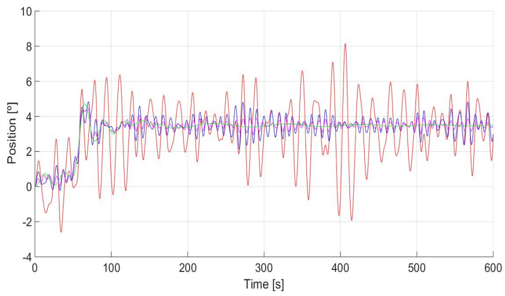
where the "perpendicular" diameter to the wind is given by:

$$D_{perpendicular} = D cos(\alpha) \quad (17)$$

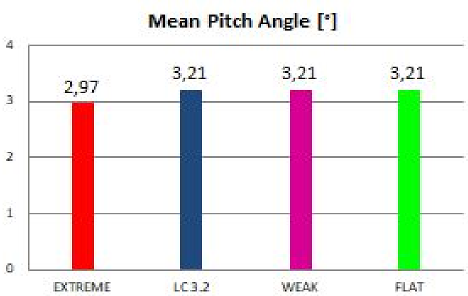
where α is the angle between the blades orientation and the vertical. So, in the end, the power could be expected to be proportional to the squared cosine. Naturally there are other factor to consider which justify the differences between both curves. The bending of blades due to their own weight; the pre-cone angle; the change in aerodynamic coefficients due to the angle between the wind and the blades; the different turbine dynamics due to different loadings in each pitch case

4.3.2 JONSWAP severity

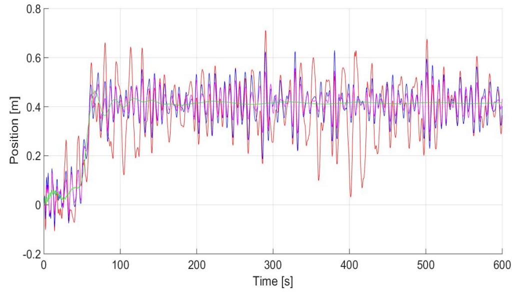
An assessment of the sensitiveness of power production in regard to sea state conditions is carried out (always in the frame of the JONSWAP spectrum). 4 different cases of increasing severity have been studied: flat (no wave at all); weak (significant wave height is half of LC 3.2); LC 3.2; extreme (the same as LC 3.5 except for the wind velocity, that is taken to be 11,4 m/s instead of the prescribed 47,5m/s). All have the same platform modelling conditions and wind resource (rated). The particularization only takes place at the wave kinematic model specifications. From the analysis of figure 5 allows for a set of important and unexpected conclusions.



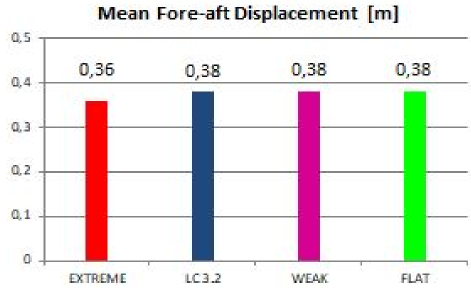
(a) Pitch



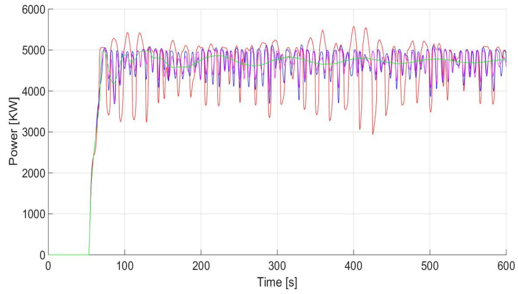
(b) Pitch mean values



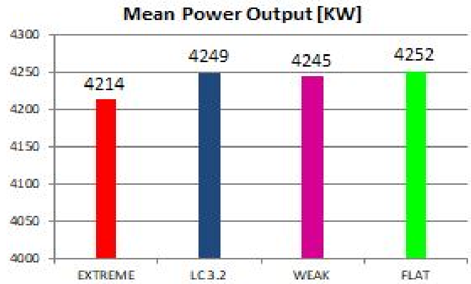
(c) Fore-aft tower displacement



(d) Fore-aft tower displacement mean values



(e) Generated power



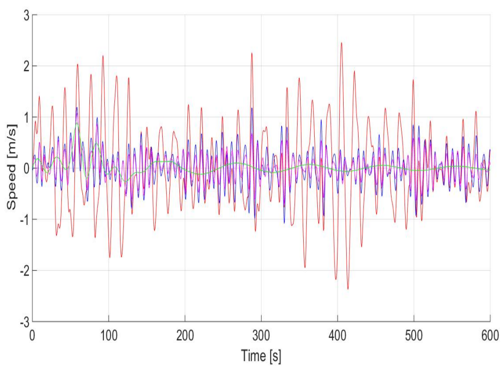
(f) Generated power mean values

Figure 5: Response analysis of four different JONSWAP intensity cases

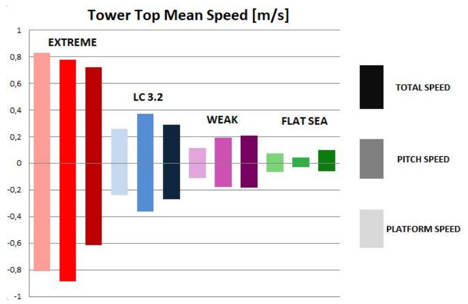
Firstly, the extremely low dependence of the mean responses displayed with the severity of the sea state. In fact, there's almost no variation of the parameters considered ranging from flat sea condition to LC 3.2.

Although the mean values are very close to each other, the same doesn't happen with the oscillations amplitude. In fact, the extreme case Pitch oscillation amplitude might be about 5 times larger than LC 3.2 and even larger if the weak case is considered. The oscillations, as will be concluded, can have a relevant effect on mean power production for some operational situations. Moreover, they are surely critical regarding structural and fatigue constraints.

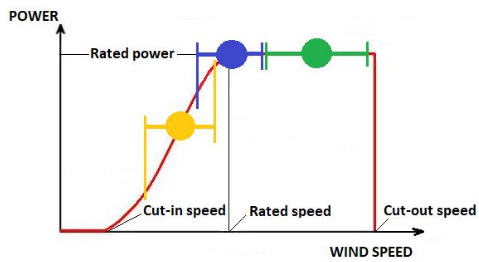
Probably the most interesting inside this figures provide is connected with the apparent contradiction with what has been previously concluded. In fact, the extreme case mean power output is smaller than the other cases, while both mean Pitch angle and mean fore-aft tower displacement have also lower values! A careful look into figure5e provides the answer. The Pitch and fore-aft oscillations clearly continuously bring down and up the power output. They do so as these movements affects the apparent wind the rotor experiences, increasing when the tower rotates/vibrates into the wind and diminishing when rotating/vibrating downwind. This change in apparent wind forces the control system to constantly adapt the operational region of the power curve, providing more or less power, respectively. As long as the lower peaks are counterbalanced with the higher peaks, the mean power output remains roughly independent of such perturbations. This happens due to a combination of two factors: oscillations amplitude and proximity to the rated power output (5000KW). In this analysis, the inflow wind velocity is kept constant, so the second factor is not changing. As the oscillations amplitude increase in the extreme case the low peaks are no longer equilibrated with the high ones due to the control system. Indeed, there isn't a limit for the low power peaks. On the other hand, the high power peaks are constrained by the control mechanisms that work towards avoiding an over rated power output. This balance of unconstrained low power peaks with a maximum (5000KW or a little bit more, when the control system doesn't actuate fast enough) power peak condition results in a reduction of the mean power production, even if the mean Pitch angle is smaller when compared with other cases. Figure 6c depicts this dynamics.



(a) Total tower top speed in the xx direction



(b) Total, pitch and platform speed, for the four cases analysed, in the xx direction



(c) Schematic different turbine operational regions

Figure 6: Possible effect of speed oscillations for different sea states in the xx direction

In figure 6b the total speed stands for total tower top speed; Pitch speed for the Pitch rotational speed multiplied by the tower top height; platform speed for the translational platform speed in the xx direction (Surge). The total speed mean amplitudes were calculated by averaging the summation of the platform Surge speed with platform Pitch speed, multiplied by the tower height. Each case has the "low amplitude" and "high amplitude", meaning they have been calculated averaging the negative and positive data from figure 6a. In figure 6c, if the the turbine is working at the yellow point (defined by the inflow wind speed) and it experiences perturbations (turbulence or changing apparent wind due to the rotor movement) of a given amplitude, the left low power peak is compensated by the right high power peak, so that in average the power production remains around the yellow circle (the exact balancing depends on the nature of the power curve in that region, i.e. if it a straight line, curved,...). The same reasoning applies for the other operational points but with different results.

In figure 6b Pitch-induced and Surge-induced mean speed are very much equivalent regarding its amplitude. Due to the oscillatory nature of both, the mean total speed, isn't simply summed and surprisingly ends up being either slightly superior or inferior to its components. If this was not the case, the energetic losses would be much more severe.

At the end of this subsection it is possible to conclude that power production is not only dependent on the mean Pitch angle but also on the Pitch and Surge oscillations mean speed.

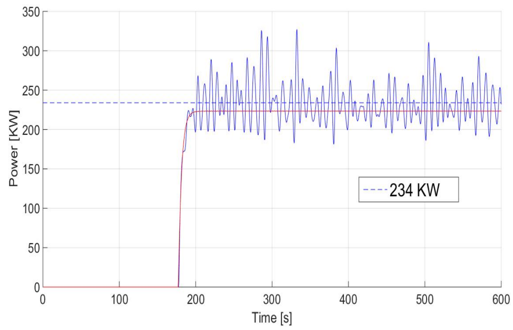
4.4. AEP calculation and comparison

The Weibull wind distribution is discretized into nine classes, as patent in figure 7, allowing the calculation of the respective power and energy outputs for both approaches.

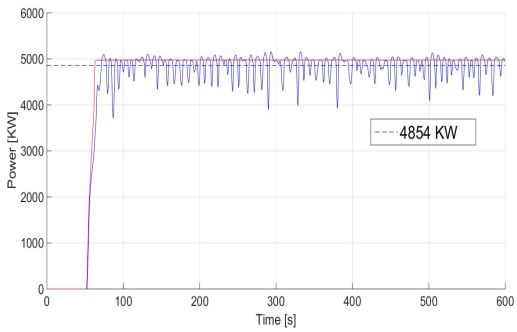
CLASS	SPEED RANGE [m/s]	MEAN SPEED [m/s]	PROBABILITY
1	3 ----> 5,5	4,3	13,7%
2	5,5 ----> 8,5	7,0	22,6%
3	8,5 ----> 10,5	9,5	15,3%
4	10,5---->12,5	11,5	13,4%
5	12,5 ----> 14,5	13,5	10,6%
6	14,5 ----> 17,5	15,9	10,3%
7	17,5 ----> 20,5	18,8	5,1%
8	20,5 ----> 23,5	21,8	2,1%
9	23,5 ----> 25	24,3	0,4%
		TOTAL	93,4%

Figure 7: Discretization of the wind distribution

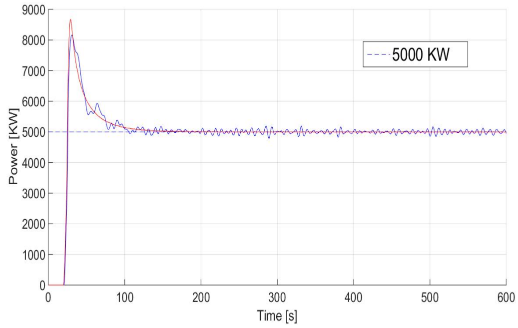
For the sake of representativeness, three simulations regarding the wind classes are presented: the case with the lowest wind velocity, class 1; the case with the highest velocity, class 9; and the rated conditions case, class 4.



(a) Class 1



(b) Class 4



(c) Class 9

Figure 8: Power output for three wind classes.

In figure 8, the blue line represents the output power. The dashed blue line represents the average power from the filled blue line from the onset of the transient-non-influenced part of the line. The red line represents a fixed and rigid tower. Three different types of situations are present: class 9 whose mean production is not affected at all. Class 4, in which the power loss is most severe, due to its proximity to rated conditions. Class 1 is the only case in which the sea-induced apparent wind oscillations carry a benefit! The reason is again the same: turbine power curve. For above operational point the curve is more vertically tilted than below the operational point. This mean that for a symmetric speed oscillation the variation in power isn't equilibrated, but has a positive output result. the opposite effect of class 4 case. An important remark concerns the wind speed class band width. As the platform dynamics matters mostly for the rated speed region, it is necessary to be careful when discretizing the wind distribution. In fact, by attributing a higher probability to a class whose speed is close to the rated, the power reducing effect might be exaggerated. A final relative difference of 2% between the two approaches is patent in figure 9.

	CLASS	1	2	3	4	5	6	7	8	9	TOTAL
AEP [MWh/year]	CONVENTIONAL APPROACH	312,03	2365,8	3967,2	5869,2	4642,8	4511,4	2233,8	919,8	175,2	24997
	PRESENT APPROACH	280,83	2280,7	3785	5697,8	4642,8	4511,4	2233,8	919,8	175,2	24527
	ABSOLUTE DIFFERENCE [MWh/year]	31,203	85,13	182,28	171,38	0	0	0	0	0	470
										RELATIVE DIFFERENCE	2%

Figure 9: Annual energy production for each wind class and total value

5. Costs and LCOE analysis

5.1. Introduction

The present chapter aims at an analysis of the main costs involved in setting up an offshore wind farm, namely the CAPEX, OPEX and DECEX.

By using the costs and energy produced, the LCOE is also estimated according to the formula:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CAPEX_0+OPEX_t+DECEX_{n+1}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (18)$$

The most important objective in the present chapter is to understand how relevant each kind of cost is in the final budget and to evaluate how strongly can the parameters variation affect the LCOE. For such, an economic model from WavEc is used. It basically receives a set of inputs such as the different project costs types, AEP, financial parameters, project life time, among other possible options and calculates the LCOE.

5.2. Sensitive analysis

5.2.1 Data and chosen parameters discussion

In order to perform the proposed analysis, data from [8] is utilized. It will be designated as standard data, in opposition to data obtained from its variation. The reference model is the semisubmersible WindFloat due to its similarities with the model used in this thesis. A discussion regarding the most crucial parameters, defines a set of key cost drivers to be analysed in the next section. The most relevant ones concerning CAPEX are: steel dependent constructions; grid and its installation; turbine. Regarding OPEX: annual operations and maintenance. Also, energy output is also looked upon as a determining factor. As for factors financially affecting LCOE discount rate and project life time are considered.

5.2.2 Results discussion

The estimated LCOE value is 130€/MWh. This value fits in the estimations provided in the literature, in [8] and [9], bringing confidence to the validity of the results. Nonetheless, as the objective of the present chapter is to discuss its variability in respect to the key cost parameters and not its exact value, a sensitiveness analysis is undertaken by changing all cost parameters by 10%, both for the increased as well as for the decreased scenario. An exception is on the turbine output power (same meaning as AEP), for which two analysis are studied: one with a 2% variation, reflecting the difference obtained in the previous chapter. For each parameter variation, all the others are kept constant.

- CAPEX

  It's a parameter whose cost constituents are expected to be subject to significant decreases (turbine cost) and to important fluctuations (steel price). Grid costs are also expected to fluctuate with a series of factors (cost of materials (copper, among others); distance to shore; wind farm layout; vessel costs (dependant on supply and demand; fuel prices;..), among others.). In face of such assumptions, the sensitive analysis is found particularly relevant. As the CAPEX is considered to be an overnight cost (no interest is incurred during the construction), the analysis shows that the influence in LCOE is linearly proportional to the standard cost. In the overall cost frame, these parameters are found to be highly relevant, specially for the construction costs. As a consequence it is hard to foresee future CAPEX evolution due to the unpredictable nature of steel prices and to the variability in grid costs, even though turbine costs present a decreasing trend.

- OPEX

  Annual maintenance operations is an important cost that is expected to be heavily dependent (over 70%) on vessel utilization [8]. Such hypothesis makes this field highly prone to be optimized with increasing wind farm sizes and other operational efficiency measures. Thus, variations that it can induce in LCOE are likely to be felt as the industry grows by diminishing its value. Also, insurance costs are naturally expected to diminish as more reliable and proven projects are set (but its influence is much smaller).

- Energy

  This parameter allows a conclusion on the relevance of the main proposed goals: the estimation of the AEP through the present thesis methodology. In fact,it's patent how a change of 2% in the AEP or turbine energy output can produce a greater or similar effect on LCOE as a 10majority of the other factors analysed. This strengthens the relevance and usefulness of committing more deeply to a more accurate estimation of the AEP, in order to better estimate a offshore wind project LCOE.

- Finance

  This is clearly the most important parameter regarding LCOE value, specially the discount rate factor. Indeed, 10% variations of its standard values leads to changes of around 5% in LCOE. This is a parameter in which positive changes are expected as the industry becomes more trustful, investors more confident, supply chain more developed,... Project lifetime is also a very relevant parameter, ranking third among all parameters. However, after a given period of time, maintenance cost and other constraints associated with extending a project lifetime might become too expensive or limiting. As such details are not included in the model, projections for a major lifetime increase are not realistic.

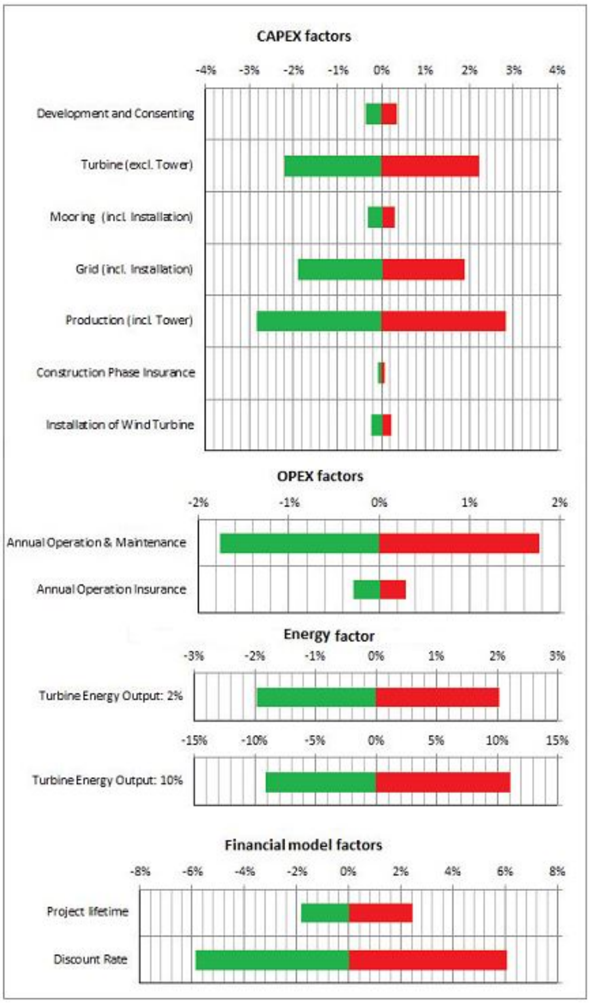


Figure 10: Impact analysis of different costs on LCOE

6. Conclusions

The platform mean Pitch value importance towards power production, strongly dependent on rotor area perpendicular to the wind flow. Fore-aft tower displacement also plays a role but is considerably less relevant.The optimal case has been found for the horizontal rotor axis position.

A low dependence of the Pitch and fore-aft tower displacement mean values while a important dependence of the mean oscillations amplitude with the severity of the sea state has been observed.

The role that tower top speed oscillations has in conjugation with the operational point in the turbine power curve. For different operational points, the impact varies. The most affected being rated conditions.

An overall difference of 2% between the conventional and present approaches regarding annual energy production estimations.

Main key LCOE increase parameters drivers have been identified for the concept studied: discount rate; production costs; project lifetime; turbine; grid. Ranking is in a descending order.

Although some costs can potentially increase, the main expectancy is for a LCOE value reduction in the upcoming years (in the assumption of continued growth and development of the industry).

7. Future work

Validation of the results presented through simulations with other codes and scaled model tank tests. Investigate the possible advantages of incorporating second-order forces, non linearities, wind turbulence and wind-shearas well asother complex modelling option not taken into account in this work. Also, extending the range of conditions from which the conclusion have been drawn. This includes combinations of different wind and wave direction; wave spectrum and wave type variations. Improve the wind discretization (more and narrower wind classes) to obtain more accurate results. Study other platforms designs and analyse the conclusions for checking if they are general or concept dependent. Finally, deepen and strengthen the economic analysis, taking advantage of more consistent information that becomes available as more projects and studies are developed.

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